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20. ferences in responses to temporal transients.

The most extensive of the three work-units dealt with motion perception by human observers. The main findings include the following: 1) Perceived speed of a moving target varies with that target's contrast and retinal eccentricity. In particular, many targets undergo illusory slowing when they appear in the periphery in the visual field. 2) Detection of a moving target is often dissociated from the ability to identify the direction in which the target moves. In particular, the accuracy with which target direction can be judged, even for highly visible targets, seems to far less good than previously suspected, 3) Relatively small amounts of training can significantly improve an observer's ability to discriminate between two highly similar directions of target motion. Moreover, this effect is well-restricted to the training direction and other, similar directions; the training effect is retained without decrement for at least two months. The results suggest that this improvement with training represents a genuine change in visual function.

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ABSTRACT

This report describes progress made from October 1, 1981 to September 30, 1983, on research supported by AFOSR-80-0246 and AFOSR-80-0246B.

During this period work proceeded on three main lines of study: 1) various aspects of visual motion perception, 2) collaborative work with AMRL/HE (Wright Patterson AFB) on contrast sensitivity and pilots' performance in aircraft simulators, and 3) individual differences in responses to temporal transients.

The most extensive of the three work-units dealt with motion perception by human observers. The main findings include the following: 1) Perceived speed of a moving target varies with that target's contrast and retinal eccentricity. In particular, many targets undergo illusory slowing when they appear in the periphery of the visual field. 2) Detection of a moving target is often dissociated from the ability to identify the direction in which the target moves. In particular, the accuracy with which target direction can be judged, even for highly visible targets, seems to far less good than previously suspected. 3) Relatively small amounts of training can significantly improve an observer's ability to discriminate between two highly similar directions of target motion. Moreover, this effect is well-restricted to the training direction and other, similar directions; the training effect is retained without decrement for at least two months. The results suggest that this improvement with training represents a genuine change in visual function.

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CUMULATIVE PROGRESS REPORT

This report describes the progress made from October 1, 1980 through September 30, 1983 on AFOSR grant 80-0246.

During this period the grant supported three lines of study:

- I) Research on Perception of Visual Motion;
- II) Collaborative Research with AMRL/HE (Wright Patterson AFB);
- III) Research on Individual Differences in Visual Temporal Responses.

In the narrative portion of this report each of these lines of study will be described separately.

Publications supported by AFOSR-80-0246:

1) Ball, K., and Sekuler, R. (1982) A specific and enduring improvement in visual motion discrimination. Science 218 697-698.

2) Ball, K., Sekuler, R., Machamer, J. (1983) Detection and identification of moving targets. Vision Research 23 229-238.

3) Bowen, R.W., Sekuler, R., Owsley, C.J., and Markell, K.A. (1981) Individual differences in pulse brightness perception. Perception Psychophysics 30 587-593.

4) Ginsburg, A.P., Evans, D.W., Sekuler, R., and Harp, S.A (1982) Contrast sensitivity predicts pilots' performance in aircraft simulators, American Journal of Optometry & Physiological Optics 59 105-109.

5) Sekuler, R., Ball, K., Tynan, P., and Machamer, J. (1982) Psychophysics of motion perception. In A. Wertheim, W. Wagenaar, and H.W. Leibowitz (editors) Tutorials on Motion Perception New York: Plenum Press. pp. 81-100.

6) Tynan, P.D., and Sekuler, R. (1982) Motion processing in peripheral vision: Reaction time and perceived velocity. Vision Research 22 61-68. [manuscript preparation and publication costs only]

I. RESEARCH ON VISUAL MOTION PERCEPTION

A. Motion Perception and Retinal Eccentricity

It has long been appreciated that the spatial heterogeneity of the retina makes a significant contribution to various characteristics of human vision. Among sources of such heterogeneity are the differential distributions of rods and cones as well regional variations in retinal receptive field size. We wondered whether the distributions of receptive fields of cells responsive to different rates of temporal modulation might affect psychophysical responses to moving targets at various eccentricities. This led us to examine two dependent variables at various retinal eccentricities. Based on the physiological data above, we hypothesized that, with sufficiently high target speeds (and correspondingly high rates of temporal modulation) psychophysical responses would be invariant with eccentricity. This work has been described in Tynan and Sekuler (1982) and in a NATO Symposium (Sekuler, Ball, Tynan and Machamer, 1982).

Our first experiment measured reaction times (RT) to motion onset for upward moving dot patterns presented at various eccentricities. The screen of the cathode ray tube (CRT) was masked by a 10 degree diameter circular aperture. A specially-constructed electronic blanking circuit could eliminate dot patterns from either the center of the screen or from its periphery. As a result, the circuit produced either a patch of dot patterns in the middle of the screen, or a central area devoid of dot patterns surrounded by an annulus of dot patterns. With either central patch or annulus, dots moving into the blanked zone disappeared; dots leaving the blanked zone reappeared.

Annuli were either 0, 2, 4, 6 or 8 degrees in inner diameter; central stimulus patches were either 2, 4, 6, 8 or 10 degrees in diameter. RTs were measured to stimulus velocities of 0.25, 1, 4, and 16 deg/sec, yielded RTs that increased steadily with annulus size. At higher velocities, RT was independent of annulus size. With central patches of moving dot patterns, patch size influenced RT only between a 2 degree patch and one of 4 degrees at the lowest speed used. For all higher velocities, RTs were invariant with patch size. Note, in addition, that in both panels, RT declines with increasing stimulus velocity.

Visual functions that depend upon spatial resolution -- acuity and very likely, RT to very slow movement -- fall off dramatically over the portion of the field studied in this experiment (LeGrand, 1967). We believe that such visual functions depend upon physiological mechanisms that respond preferentially to lower temporal frequencies. The rapid decline in psychophysical spatial resolution is consistent with the hypothesis that cells responsive

to lower temporal frequencies. The rapid decline in psychophysical spatial resolution is consistent with the hypothesis that cells responsive to lower temporal frequencies are more likely to have receptive fields in the center of vision. RTs to moderate speeds of motion show no decline over this same range of eccentricities. Very likely, cells with appreciable sensitivity to higher rates of temporal modulation participate in the detection of such motion. The invariance in RT with eccentricity is consistent with the hypothesis that cells with receptive fields in the periphery respond to higher temporal rates.

In a second, related experiment, we measured to perceived speed of targets at various eccentricities. These measurements were made for targets covering a range of speeds. Stimuli were random dot patterns moving upward within a strip 28 degrees high by 4.7 degrees wide. Observers matched the apparent speed of a target at each of several eccentricities with the adjustable speed of similar dot patterns presented in the center of vision. Test targets could be presented immediately to the left of the fixation point, or at various distances from it: 7.5, 15, 22.5, and 30 degrees. The duration of any movement varied randomly between 1.5 and 2.5 seconds, making it impossible to judge velocity simply from the distance traveled by any particular element in the pattern. Target velocities of 0.25, 1, 4, and 16 deg/sec were factorially combined with the five eccentricities.

No measurements could be made with the slowest movement, 0.25 deg/sec, at eccentricities beyond 7.5 degrees because, on more than half the trials with such eccentricities, the 0.25 deg/sec stimulus appeared stationary, a phenomenon reported by Lichtenstein some years ago (1963). The results of the experiments can be summarized simply: eccentrically-viewed dot patterns appear to move more slowly than do centrally-viewed ones. This slowing effect increases with eccentricity and decreases with target speed.

In both experiments, psychophysical responses to slowly moving targets change rapidly as a function of eccentricity of presentation. Also, in both cases, psychophysical responses to rapidly moving targets are nearly invariant with eccentricity of presentation. These experiments sought to test an hypothesis about psychophysical parallels to the retinotopic distributions of neural cells whose temporal responses differ from one another. The effects obtained seem to parallel the retinotopic distributions of neural cells that respond best to low rates of temporal modulation and of neural cells that respond best to higher rates of modulation.

Obviously, there needs to be a follow-up with other kinds of temporally modulated stimuli at various eccentricities. Such stimuli should include spatially localized targets whose eccentricity can be specified more precisely.

But, follow-ups aside, the work just described does offer an important lesson that others should consider.

Although many psychophysical theorists have found it convenient to dichotomize visual mechanisms into "sustained" and "transient", the visual system very likely does not itself always respect this bipartite classification. But it is easy to see how one could be misled into believing such a dichotomy characterized the structure. For example, if we had considered only extreme speeds, there would have been a clear difference in visual response as a function of eccentricity. This clear separation would have been consistent with a dichotomy. However, if we also take account of intermediate speeds, responses define a continuum between these extremes. For such intermediate velocities, psychophysical responses are neither invariant with eccentricity nor do they exhibit as rapid a decline as do responses to the most slowly moving targets. As we have been so well reminded by Kelly (1977), stimuli for many visual responses must be defined on a continuum of both spatial and temporal dimensions.

B, Detection vs. Identification of Moving Targets

Observers in most detection experiments know precisely what sort of targets they will be asked to detect. In fact, that knowledge aids their performance so that if they are not well informed, performance declines. For example, the detectability of a moving target decreases considerably if the observer is uncertain about its direction of movement (Ball and Sekuler, 1980). In most of the work on direction uncertainty supported under AFOSR-80-0264 and its predecessor grant, observers had to judge only the presence or absence of a moving target: no judgement about direction was required. But in one set of experiments, we told observers after each trial what direction the stimulus motion had actually taken (Ball and Sekuler, 1981). Often observers reported surprise since they had perceived a direction that differed considerably from the one we had presented.

We decided to follow up our subjects' reports exploring how judgments of direction of motion might actually be dissociated from the ability to detect a moving target. Studies reported here differ from our earlier work in that we sought not only variables that control detection of moving targets but also variables that control the ability to identify the direction in which these targets appear to move. This work (published in Ball, Sekuler and Machamer, 1982) represents a step toward a model of the complete neural code underlying the perception of direction.

One element in our rudimentary model is the assumption that motion is detected when at least one directionally selective filter generates a response of sufficient magnitude. Like other sensory mechanisms, these filters are stochastic rather than deterministic; the same input, on different occasions evokes responses in any filter that vary from

one occasion to the next. But explaining detection in this way leaves a major question unanswered: what role do these filters play in our ability to distinguish one direction of movement from another?

To help formulate an answer, we turned to studies in which observers were asked to detect and discriminate sinusoidal gratings simultaneously. In one such study, Watson and Robson (1981) proposed that a collection of detecting mechanisms sharing a common selectivity to spatial frequency may signal the presence of that particular stimulus attribute. In other words, if a mechanism responds most strongly to one direction and if the mechanism always indicates to the observer motion in that preferred direction, then the direction of a moving grating should be reported as accurately as its presence or absence (Watson and Robson, 1981). In neurophysiology, this is often termed the "labelled lines" hypothesis.

Transposing into the domain of motion perception, suppose that observers can distinguish the responses of different direction-selective mechanisms from one another. When the observer cannot tell ahead of time which of two directions of motion might occur and the two directions are always detected by different mechanisms, then the observer ought to be able to identify the direction presented. That is, the direction should be correctly identified whenever the stimulus is detected. But if the two possible directions are often detected by the same direction-selective mechanism, there are likely to be confusions about the direction presented.

Our first experiment established baseline measurements for the two tasks we planned to use later: detection of a moving target and identification of direction. Two variables were of particular interest to us, the contrast and duration of the moving targets.

In the first experiment we restricted our stimuli so that all directions presented were within 30° of one another. Previous data (Ball and Sekuler, 1980) demonstrated the broad tuning of direction-selective mechanisms. Using a narrow band of possible stimuli increased the chances that all of our stimuli would evoke non-trial responses from a single, common directionally-selective filter. This would allow us to examine detection and identification under conditions in which accurate identification should be most difficult.

Three observers with normal, uncorrected vision participated. Two of the observers (K.B. and J.M.) were experienced psychophysical observers and know the research's purpose. The third observer (J.E.) was naive.

Stimuli were isotropic random dots presented on a cathode ray tube (CRT) under computer control.

For both detection and identification tasks, movement in any one of 31 directions was equally likely. The directions we used spanned the range of 75° to 105° (90° being upward

movement). Directions were presented in random order so that the observer never knew precisely which would be presented.

The contrast of the pattern was defined as the ratio of the incremental luminance of the dots to the constant, veiling luminance. Stimuli could be presented at contrasts ranging from 231 to 0% (veiling light alone). The second variable, duration of stimulus presentation, spanned the range between 62 and 500 msec.

The detection task used a 2-alternative forced-choice procedure. Each trial consisted of two intervals separated by 200 msec and defined by a co-extensive, high pitched tone. One interval contained a pattern of random dots moving at 4 deg/sec; the other contained no stimulus (veiling light alone).

The identification task differed from the detection task in several ways. In the identification task a trial consisted of just one interval during which a moving stimulus was always presented. The observer's job was to judge, to the nearest degree, the stimulus direction. A protractor around the edge of the display aided the observers in reporting the perceived direction.

From the percent correct responses for each contrast duration combination we determined the corresponding value of d' . Identification results were summarized as r , the linear correlation between perceived and actual directions.

Under optimal visibility for this apparatus, observers were able to report direction of movement with a fair degree of accuracy. At this high contrast observers were able to detect the presence of the moving target 100% of the time. Also at this contrast observers K.B. and J.M. were able to report the direction of movement as accurately with a duration of 125 msec as they were with a 500 msec display ($r=0.91$, mean error = 2°). At a contrast = of 7% observers achieved near perfect detection of movement at all durations. However, even at 500 msec presentation length both J.M. and K.B. made many highly erroneous judgments of direction. For example the mean error was 6.7° for each observer, with individual errors on a given trial as high as 30° .

So when the possible test directions are highly similar there appears to be a large discrepancy between the ability to detect the presence of a moving target and the ability to identify the direction of the target.

Our next experiment determined if two directions of motion could be perfectly distinguished from one another when each was near its contrast threshold. This experiment compared detection and identification performance for a moving target concurrently for various differences between two equally likely directions of motion. Our goal was to determine the critical separation between directions at which point direction of motion could be distinguished just as well as its presence could be detected. This separation

would then be indicative of the range of directions to which a single direction-selective mechanism is sensitive (Watson and Robson, 1981).

A 2 x 2 AFC procedure was used (Nachmias and Weber, 1975). Each trial consisted of two 500 msec intervals demarcated by tones and separated by 200 msec. A random dot stimulus, moving at 4 deg/sec, was presented in just one of the two intervals. During the other interval the display remained blank except for the veiling luminance. The interval, first or second, which would contain the stimulus was varied randomly. On each trial the direction of motion was also picked randomly from a pair of alternative directions. The alternatives were constant for any block of 50 trials but varied randomly between blocks. One possible direction moved to the left relative to upward (90°), the other an equal amount to the right. In any block, pairs of alternative directions differed from one another by either 30° , 60° , 90° , 120° , 150° or 180° .

The observer judged which interval, first or second, had contained the moving dots (detection response); and then judged whether the stimulus had moved to the left or right relative to upward (identification response). Detection judgments were always made first since preliminary practice trials had shown that the interval judgment was frequently forgotten when directional responses were given first.

Contrast of the dot pattern was held constant across all of the conditions tested and each observer received extensive practice on the task prior to testing. During this time, contrasts were identified that would produce moderate detection levels for the three observers. Detection scores decline as direction uncertainty is introduced and therefore previously used contrasts produce lower detection scores. For K.B. and J.M. the contrast value chosen was 5% for J.E. it was 8%.

As the difference between the two possible directions of motion increases, detection performance declines. This decline has been well documented before (Ball and Sekuler 1980) and is associated with increasing direction uncertainty. Second, note that as detection performance decreases the observers' ability to currently identify the direction of motion increases. An analysis of variance substantiated a significant interaction between the detection and identification tasks ($F=12.86$, d.f.=5. $10.P<0.01$). The functions for detection and identification cross when the two alternative directions differ by 150° . At that separation detection and identification performance are equal: from 150 to 180° separation, neither kind of performance changes much.

Tanner (1956) developed a method for predicting recognition data from detection data. We used his model to provide another test of the estimated width of tuning of directionally-selective mechanisms. Tanner's model incorporates

an estimate of the correlation between psychophysical responses to two stimuli. Using vectors in a multi-dimensional space to represent the responses, the correlation (\underline{r}) between the two sets of responses is numerically identical to the cosine of the angle between the vectors. For example, if psychophysical responses to two stimuli are uncorrelated ($\underline{r}=0.0$) in the multidimensional space, θ , the angle between vectors corresponding to those responses, is 90° and the associated cosine is 0.0.

The two alternative directions become more different, θ increases, indicating that mechanisms detecting the two directions have less overlap in sensitivity. When the two possible directions differ by 120° or less, mechanisms used to detect them are correlated by some extent; when the directions are separated by at least 120° - 150° , they are detected by mechanisms that are independent.

We wished to compare our estimates to those obtained from other experimental procedures. We found seven previous experiments on motion perception that could be used to estimate breadth of tuning.

Three studies have examined shifts in perceived direction. For example, Levinson and Sekuler (1976) measured the shift in perceived direction following a 3 minute exposure to a pattern of adaptation dots. The shift in perceived direction decreased as the adapting direction became less similar to the test direction. Some interaction remained until the two directions differed by $\pm 65^\circ$, indicating that direction-selective mechanisms span about 130° . Marshak and Sekuler (1979) measured the error in perceived direction as a function of the separation between simultaneously presented directions. They found interactions between the directions up to a separation of 135° . Mather and Moulden (1979) also measured a simultaneous direction shift and obtained similar results. Ball and Sekuler (1979) used a masking procedure in order to determine which directions would mask an upward moving target. They found that directions as much as 65° or 70° to either side of the test direction produced masking. Mather (1980) worked with the motion after-effect produced by two directions simultaneously presented. He found that the two directions had to be separated by approximately 150° before they became independent. Finally, Ball and Sekuler (1980; 1981) performed two direction uncertainty experiments to estimate the width of direction-selective mechanisms. In the first (1980), they looked at the increase in reaction time as two directions became more and more dissimilar. Reaction times increased to a maximum at a separation of 120° . The second experiment determined when a direction cue presented prior to the stimulus was beneficial to performance and when it became detrimental. Cues were of no benefit or produced a slight loss in sensitivity when they differed from the test direction by $\pm 75^\circ$. This indicates an overall width of 150° . All

of the results are remarkably consistent: direction-selective mechanisms have a width of 120° - 150° .

According to the model of Watson and Robson (1981), two stimuli that are detected by independent mechanisms will also be perfectly discriminated from one another. Assuming directionally-selective mechanisms some 120° - 150° wide, our data agree with this model.

Although a minimum of only three non-overlapping mechanisms are needed to span 360° , we must emphasize that this does not mean there are only three different direction-selective mechanisms. Three is simply the minimum number required to code direction; a larger number of directionally-selective mechanisms, arrayed with sufficient density along the direction continuum, would be required to account for the fact, that under proper conditions, direction difference thresholds can be as small as 1° - 2° (Ball and Sekuler, 1979).

Our results show that under most circumstances there is a large discrepancy between the ease of seeing a moving stimulus and the ability to assess its direction. The difference in the two tasks suggests that arranging conditions to produce good detectability of a target will not insure good identifiability. This discrepancy may be particularly important in operational settings.

This research also clarifies clear why observers in previous experiments (Ball and Sekuler, 1980) were occasionally surprised when told what direction we had presented. Unless the separation between possible directions of motion is extremely great, observers may see a moving target but still not know in what direction it is moving.

C. Training and Perceptual Enhancement

In the past decade, a great many behavioral studies of vision and visual perception have been strongly influenced by findings in visual physiology. Although this has been a generally fruitful influence, it has not been without cost. Some costs have been discussed elsewhere; others may be less obvious. Foremost of the more familiar costs has been a tendency to oversimplification (Uttal, 1981). This has produced any number of vague speculations on the connection between some particular psychophysical phenomenon, on the one hand, and some "parallel" physiological result, on the other.

But there have been other, less obvious drawbacks to this dominant approach to vision. For example, the elegant and intriguing work on experiential influences on the neonatal development of the visual system (Movshon and Van Sluyters, 1981) has made vision researchers view the visual system as an assemblage of elements whose properties were essentially stable once some critical developmental period had passed. Arguably, this view may have discouraged examination of the plasticity of adult, human vision. Whatever the cause, the number of carefully done studies

of "practice" or "training" within a vision science framework has been quite small. This is not to deny that there have been virtually innumerable studies of "perceptual learning," but rather to point out that such studies results can typically be understood as depending upon one or more of the following: improved ability to pick out features that distinguish one visual target from another (Fiorentini and Berardi, 1981), a change in the way an observer uses verbal labels to describe his experience, heightened attention or arousal, or a change in the observer's criterion (DeValois, 1977). If a study of perceptual learning could be explicated in terms of any or all of these hypotheses, there would be no need to postulate that practice had had an effect on the visual system itself. Supported by AFOSR-80-00246 we undertook research that shows vision, motion perception in particular, can be improved significantly under circumstances that cannot be easily explained in terms of any of the "artifacts" listed above. The initial results of our efforts have been published in Ball and Sekuler (1982).

Since in previous work motion perception revealed considerable plasticity, we set out to train an observer's discrimination of the direction of moving targets. Prior to training, we measured how well observers discriminated small differences in direction of motion. Discrimination was assessed around eight different directions: 0 (rightward), 45, 90 (upward), 135, 180, 225, 170, and 315 deg. Hereafter, we refer to directions 0, 90, 180, 270 as "cardinal" directions: and 45, 135, 225, and 315 as "oblique directions."

Stimuli were bright, spatially random dots moving along parallel paths over the face of a cathode ray tube at 10 deg/sec. At any one time, about 400 dots were visible within an 8 deg, circular aperture. The dots, and their movement, were highly visible: the luminance of the dots was approximately 50 times that required for them to be just seen against a constant veiling luminance of 2 cd/m². Opposite ends of the display were linked electronically so that dots disappearing at one side wrapped-around, to reappear at the opposite side. Observers viewed the displays binocularly, fixating a dark, stationary, central point. To guard against the possibility that observers might learn to identify details of our display, a new array of spatially random dots was used every 50 trials.

Each trail consisted of two, 500 ms intervals. This pair of intervals was separated by a 200 ms period during which only the uniformly illuminated cathode ray tube was visible. Two equiprobable typed of trials, "same" and "different", were randomly ordered. On "same" trials, motion took the same direction during both intervals; on "different" trials, motion in one interval was in a direction differing by 3 degrees from that of the other interval. The observer viewed both intervals and judged the two directions "same" or "different".

A block of 50 trials was characterized by one, standard direction. This direction appeared in both intervals of "same" trials and in one interval of "different" trials. In the remaining interval of "different" trials, a random choice was made to present motion either 3 degrees clockwise or 3 degrees counter-clockwise of the standard direction. Whether the first or second interval contained the standard direction on "different" trials was also randomly determined. A tone after each correct judgment gave immediate knowledge of results.

The main experiment required seven sessions over 10-12 days. In sessions 1, 4, and 7, discrimination performance was measured for all eight directions. The order of testing was separately randomized for each session and observer. In sessions 2, 3, 5, and 6, an observer trained on just one of the eight directions, cardinal and oblique. At the start of the experiment, a different training direction was assigned each observer, who retained that assignment throughout the experiment. During a training session, an observer made 500 "same-different" judgments (10 blocks of 50 trials) with the assigned direction. For both training and test sessions, observers were rewarded with 2 cents for each correct response; 1 cent was deducted for each incorrect response.

Responses in a block of trials were reduced to a pair of proportions: the proportion of "different" trials correctly identified as such (hits), and the proportion of "same" trials misidentified as "different" (false alarms). These proportions were converted into d' , a measure of discrimination performance. This measure grants immunity against spurious performance changes that would follow systematic shifts in the observers' use of the two response categories, "same" and "different".

Discrimination was much better for the cardinal directions (up, down, left or right) than for the oblique directions. Several other findings are of particular importance. First, with the training direction, performance showed a significant and linear improvement over the seven sessions ($p < .01$). This gradual, steady improvement was seen for all observers and suggests an underlying process different from the sudden improvement produced when observers learn to pick out the distinctive, spatial features of a stimulus pair. Second, training was not effective for the three directions most different from the training direction, including the direction opposite the training direction ($p < .01$). Note however that improvement with the trained direction does not come at the expense of diminished performance with the opposite direction. Third, training with oblique or cardinal directions produced comparable improvements ($p = .12$). One additional is worthy of attention: although discrimination improves at either direction 45 deg from the trained direction, the improvement was significantly less than that at the

trained direction itself ($p < .01$).

This enhancement of discrimination endured in the absence of more training. Two retests were made following training, at 3 and 10 weeks. Six of our original eight observers were available for the first retest; and 4 were available for the second. The outcome was clear: virtually all of the original improvement was retained. Moreover, the improvement continued to be sharply restricted: the difference between trained direction and the direction opposite was just as large as it had been at the end of training.

But would improved discrimination also alter other aspects of motion perception? To test this, we determined the minimum dot luminance necessary for them to be just barely visible (that is, their detection threshold). Thresholds were measured with the dots moving at 10 deg/sec, the training speed. Three directions were tested: the training direction, the direction opposite, or a direction 45 deg from the training direction. Luminance thresholds were determined with a two-alternative forced-choice tracking method. On each trial, moving dots were presented in one of two, 500 ms intervals; only the uniformly lit display was visible during the other interval. The observer had to identify the interval during which dots had been presented. A tracking procedure located the threshold luminance, the luminance enabling correct identification on 75% of the trials. Thresholds were determined in our second group of eight observers on the day after each one's seventh experimental session. The earlier observation that training persisted for many weeks, made us confident that these observers were being tested at a time when they still retained the effects of training.

There were no reliable differences among the contrasts required to see movement in the training direction versus those needed to see motion in either of the other two directions (12.5% vs. 12.5% and 13.1%, $p > .50$). Apparently, training can improve discrimination of direction without affecting detection.

A great deal remains to be done with this potentially rich paradigm. For example, we need to know whether direction discrimination is actually the only aspect of motion perception that lends itself to training. Are there conditions under which detection or other aspects of motion perception might not also be susceptible? Finally, to what extent are features of perception unrelated to motion also susceptible to training? One major thrust of our future efforts will be the pursuit of the limits to which training can enhance vision. Again, the emphasis will be conditions that exclude indirect or artifactual explanations of whatever enhanced visual performance may be obtained.

D. Repulsion and inhibition between moving contours

During 1980-81 Captain William Marshak of the U.S. Air Force completed his Ph.D. research in our laboratory. Marshak, whose research was aided by AFOSR-80-0246, has gone on to teaching duties at the Air Force Academy. Marshak's dissertation research led to the development of a model for the perception of visual motion. The most significant result in the dissertation is that, under many conditions, two or more directions of motion can be combined so as to make the combination indistinguishable from a single direction of motion. This and related effects led Marshak to develop a three-stage vector model of motion perception, incorporating contrast-dependent processes including lateral inhibition.

Marshak discovered that at threshold, two or more directions of motion cannot be discriminated from one direction over separations of direction greater than 16 and less than 60 degrees at threshold contrast. In other words, the multiple directions produce a percept indistinguishable from a single direction. When the same stimuli are presented at six or more times threshold contrast, another kind of perceptual error occurs: the component directions are seen separately but their perceived directions repel one another. [This phenomenon was described in some detail by Marshak and Sekuler, 1979].

In a series of experiments, contrast, directional content, pattern content and velocity determined the conditions under which directions of motion summate or repel one another. Inhibition among motion sensitive units is the presumed underlying cause of these perceptual errors. Stimulus changes increasing inhibition enhance repulsion; changes decreasing inhibition enhance summation.

A three stage, vector model was proposed to explain these errors in directional perception. The model's first stage of direction processing is excitation of directionally sensitive units. Such units may be portrayed in polar coordinates as vectors whose orientation is their optimal direction of sensitivity and whose length indicates the amount of activation. The directional tuning of these units subserve motion detection but contain too diffuse a distribution of excitation to determine direction alone. The second stage of motion perception is an inhibitory process limiting the distribution of excitation to units whose sensitivity is close to the direction of motion and suppressing activity in units sensitive to other directions. In the third stage, all remaining excitation is processed by a decision mechanism that determines the perceived direction of motion. Two decision processes, a peak detection and a vector summing process, were considered, with little to choose between the two. These stimuli and paradigm developed in this research were later adapted for use by Williams and Sekuler (1984).

II. COLLABORATIVE RESEARCH WITH AMRL/HE

During this report period AFOSR-80-0246 supported two a research collaboration between Captain Arthur Ginsburg's group at Wright-Patterson and our own group at Northwestern. Although both were exploratory in nature, each was important enough to merit some comment here.

A. Normative Work on Contrast Sensitivity. It has been apparent for some time that it may be useful to supplement other measures of contrast sensitivity. These measures require the determination of threshold contrast values using sinusoidal gratings as stimuli. If a sufficient range of spatial frequencies is examined, a well-defined Contrast Sensitivity Function (CSF) can be described. Ginsburg (1980) and others have argued that the CSF is a good predictor of visual function in a variety of operational environments. These claims are just beginning to be tested. One prerequisite for the widespread use of CSF to describe visual status is a large set of normative data on CSF. Until now such normative data have been lacking: the largest sample previously reported in the literature represents data from only 30 or so individuals. In addition, previous measurements have been made in laboratory environments, raising some question about the feasibility of testing 1) inexperienced observers, and 2) performing such tests under field conditions.

To answer questions about the feasibility of such testing as well as to provide needed normative data, we collected data at two sites. The first was the Annual Dayton Air Fair, at which we collected data from nearly 150 attendees of the Fair. The second was the Air Force Museum in Dayton, at which we collected data from approximately another 150 visitors. Our instruments were a pair of matched micro-processor driven Optronix Corporation Vision Testers with video displays. Several things of note emerged from these efforts. First, it clearly is possible to perform rapid and reliable measurements of contrast sensitivity on naive, randomly chosen observers. Second, compared with measures of acuity on these same observers, the CSFs covered considerably larger range of individual differences. Third, with low spatial frequency gratings (large bars), an observer's sensitivity measured with stationary gratings is not predictive of that observer's sensitivity to the same gratings presented in movement. In marked contrast, with high spatial frequency gratings sensitivity to moving and stationary gratings were demonstrated by our work previously with other kinds of targets, that or certain speeds of movement, the visibility of some target cannot be predicted from any measure of the same observer's ability to detect

non-moving targets.

B. Contrast Sensitivity and Simulator Performance. Visual acuity, does not always predict how well observers will see targets in operational settings. An observer's contrast sensitivity function (CSF) can predict his ability to see virtually all targets that he may encounter, including spatially complex objects such as letters and aircraft silhouettes.

Previous studies (limited to static conditions), did not test the connection between CSF and complex visual tasks. Our study attempted to relate individual pilot's contrast sensitivity to a complex task, air-to-ground target detection in a visual flight simulator.

In January 1981 a small contingent from AMRL/HE and one from Northwestern began a second project. With the cooperation of the personnel at Williams Air Force Base and Colonel Needham, we made coordinate measures on several Air Force pilots and instructor pilots on 1) visual acuity, 2) contrast sensitivity, and 3) detection and recognition in specially designed mission-scenarios in the F-16 simulator. We encountered a number of logistical difficulties during our stay at Williams, including serious instabilities of the simulator display.

Fortunately, these problems were resolved, allowing us to conduct a full-scale study at Williams AFB [reported in Ginsburg, Evans, Sekuler and Harp, Contrast sensitivity predicts pilots' performance in aircraft simulators, American Journal of Optometry & Physiological Optics 1982 59 105-109].

During our second visit to Williams AFB we tested 11 instructor pilots on active duty. Their mean age was 27.4 years; distance corrections, if any, were worn during all testing.

Conventional visual acuity was measured using a projected chart with Sloan letters at 10 ft. Acuities were expressed as minimum angle resolvable (MAR), in minutes of arc. Acuity measures were made under photopic (2102 cd/m²) and scotopic (.21 cd/m²) luminance. Fifteen minutes adaptation was allowed before scotopic testing.

Contrast sensitivity measurements were generated automatically by a portable, microprocessor system (Optronix Corp. Series 100 Vision Tester). Targets were vertical sinusoidal gratings presented on a video display. The Vision Tester controlled spatial frequency, contrast, and rate of movement. At 9 ft all gratings subtended 4 by 5 degrees. CSFs were obtained at luminances of 150 and 0.15 cd/m². Contrast thresholds were measured for 6 stationary gratings (1, 2, for 6 stationary gratings (1, 2, 4, 8, 16 and 24 cycles/degree) and 3 moving gratings (1, 4 and 8 cycles/degree all drifting at 5 sec). An ascending method of limits was used. On each trial, the grating's contrast was set at a random sub-threshold contrast and increased

steadily until the observer pressed a button to indicate that the grating had become visible. This procedure was repeated three times for each grating.

The air-to-ground detection task was run simultaneously on two panoramic video-based simulators of fighter aircraft, each using computer generated imagery. One simulated an F-16's cockpit view and controls, the other an A-10's. Only 2 of the 11 pilots had any previous F-16 simulator experience; none had flown the actual aircraft. During a typical landing, following a 1 minute "flight" over flat terrain with background mountains, pilots were required to detect a MIG aircraft having 37% contrast and situated at the near end of the runway. This target was present during 3 of every 4 missions each pilot "flew". Since the presence of the MIG was random, the pilot could never be sure, as he approached the runway, whether he would have to maneuver to avoid hitting the MIG.

Landings were made in different conditions of simulated visibility: daytime, nighttime and fog. Mean luminances of the landing areas were 3.42, 1.70 and 1.9 cd/m², respectively. Four missions were flown in each condition.

The pilot "flying" the F-16 simulator depressed the nosewheel steering button when the MIG on the runway was first seen and then continued landing. The pilot in the A-10 pilot was a passive observer of the landing approach. However, the A-10 pilot did have to depress the nosewheel steering button as soon as he saw the MIG on the runway. Any differences between detection ranges of A-10 and F-16 pilots would be an indication of flying workload. We postpone consideration of this difference to a fuller report of our study. Here, we confine ourselves to data from the A-10 simulator.

All pilots "flew" both simulators; half flew the F-16 first and the other half flew the A-10 first. Total time in each simulator was 30 to 40 minutes per pilot. A computer monitored and stored flight data for later analysis. Data included landing speed, aspect angle (the angle of the pilot's view with respect to the target), and the detection slant range, the distance at which the MIG became visible.

After "flying" all his missions, each pilot examined a set of four photographs showing the MIG from different distances. The visual appearance of the MIG ranged from a faint "blob" (at the greatest distance) to a distinct, L-shaped profile with discernible vertical stabilizer (at the shortest distance). After testing, pilots identified the photo that best approximated the way the MIG appeared when detected.

The mean visual acuity of the pilots was 0.73 minarc (S.D. 0.16) and 1.83 minarc (S.D. 0.19) for photopic and scotopic conditions, respectively. The Pearson product moment correlation between the two measures of acuity was +0.01. This correlation was not statistically significant,

in concert with previous studies.

Because the simulators required us always to test with clear visibility first; small, non-systematic differences between the visibility conditions represent a complex mixture of visibility and possible practice effects. Here, we present results from the low visibility condition.

From their identifications of the MIG photos taken at various distances, our pilots could be grouped into three categories, each using a qualitatively different criterion for detection of the MIG. Pilots who detected the MIG when it appeared as a circular blob had a mean slant detection range of 6865.4 feet (S.D. = 2713.8); pilots using an elliptical blob appearance as the basis for detection had a mean detection slant range of 4954.0 ft (S.D. = 1385.4); pilots who used a distinct, L-shaped profile with a discernible vertical stabilizer had a mean slant detection range of 4815.1 ft (S.D. = 1541.1). For pilots with the shortest mean slant detection range, the MIG, when detected, subtended 33 by 10.7 min (length by height). For pilots with the longest mean slant detection range, at the moment of detection the MIG subtended 24 by 7.5 min.

We examined the correlations between an observer's slant detection range and two other measures: contrast sensitivity and visual acuity. Several of the correlations with contrast sensitivity were highly significant, especially at the low and middle spatial frequencies. The strongest correlations were between the peak region of scotopic contrast sensitivity and the slant detection range ($r = 0.83$, $p < .01$). There was no reliable relation between visual acuity and slant detection range ($r = 0.13$ for photopic acuity; $r = -.13$ for scotopic acuity).

Photopic contrast sensitivities are similar to those reported elsewhere. As reported previously, correlations between acuity measures and contrast sensitivity tend to be low. For example, two of our pilots had similar photopic acuities but peak contrast sensitivities that differed by factors of 1.4 and 2.2 under photopic and scotopic conditions, respectively. In addition, though both used the same detection criterion, the pilot with higher contrast sensitivity detected the MIG from a distance of 2.4 times that at which his less sensitive colleague did. This difference is consistent with previous predictions.

Under our experimental conditions, a pilot's contrast sensitivity predicts his ability to detect a small, semi-isolated air-to-ground target; the pilot's visual acuity does not.

At the moment of detection for the pilots with the longest mean detection range, the target MIG subtended at last 24 by 7.5 min of arc. It is well established that targets this large are detected by mechanisms in the visual system that are not involved in detection of targets requiring acuity of 6/6 (20.20) or better.

Since a pilot was "flying" toward the target, the

MIG's retinal image changed size over time. But because our target was below threshold and its image below threshold and its image size changed gradually and slowly (about 4% per second), it is unlikely that pilots detected the MIG on the basis of size changes.

Training can alter an observer's use of visual information. If pilots who detected the MIG when it appeared as a distinct, L-shaped profile could be trained to detect the MIG when it appeared only as an indistinct blob, then their detection range would be increased by as much as 50%. This increase in detection range could reduce workload for many of pilots and increase their operational performance.

Our results are most relevant to visual performance in fighter aircraft. Contrast sensitivity may have predictive value for other complex visual tasks in aviation and motor vehicle operation. Finally, our results raise new doubts about the relation between standard clinical tests of vision and patients' performance in complex visual environments.

III. STUDIES OF INDIVIDUAL DIFFERENCES IN VISUAL TEMPORAL RESPONSES

Temporal brightness enhancement (the Broca-Sulzer effect) is a perceptual phenomenon in which a pulse of light of approximately 50-150 msec appears brighter than pulses that are either shorter or longer. Though this phenomenon has been known and studied for more than a century, the relatively small number of observers tested during that time seems, in retrospect, to have obscured an important fact: the existence of systematic and stable individual differences. Since our group has a long-standing interest in individual differences in perception we decided to collaborate with Dr. Richard Bowen (Loyola University of Chicago) on a large scale study. The results of this collaboration have now been published (Bowen, Sekuler, Owsley, and Markell 1981).

First, some background to our study. Bowen and Markell (1980) studied the occurrence of temporal brightness enhancement in a large sample (n=80) of naive observers and found systematic individual differences. Observers compared the brightness of equal-luminance short and long pulses differing by a fixed duration. Temporal brightness enhancement was studied under two conditions of pulse asynchrony, simultaneous onset of the pulses to be compared or simultaneous offset.

Bowen and Markel identified three distinct classes of observers. One class of observer (designated Type A and representing 57.5% of the sample) exhibited temporal brightness enhancement for both simultaneous onset and simultaneous offset of the pulses to be compared. In other words, for both asynchrony conditions at least one pulse duration could be found (in a range of 50-150 msec) that was judged brighter than shorter or longer pulses. Type B observers (32.5% of the sample) perceived brightness enhancement for simultaneous offset conditions but not for simultaneous conditions. Type C observers (10% of the sample) did not perceive brightness enhancement under either asynchrony condition.

In the present study, we first classified groups of observers as Type A, B, or C based on their brightness vs. duration functions. We then tested these observers on three other tasks requiring psychophysical responses to temporally modulated targets. The first required observers to estimate the magnitude of the brightness of single pulses of varying duration; the second assessed sensitivity to full-field sinusoidal flicker; and the third measured contrast sensitivity for moving sine-wave gratings.

These measures were intended to test hypotheses about the basis for the differences among classes of observers. Our battery of psychophysical tasks was chosen to distinguish between perceptual criteria and neurophysiological responses as sources of individual differences in brightness perception.

The battery consisted of (1) classification of observers by simultaneous brightness discrimination, (2) magnitude estimation of brightness for pulses of varying duration, (3) measurement of the temporal MTF (modulation transfer function), and (4) measurement of sensitivity to moving sinusoidal gratings. If observers' neurophysiological responses to pulses of light differed, we would expect psychophysical differences in magnitude estimates of pulse brightness, flicker MTFs, and possibly, sensitivity to moving gratings. Several outcomes could be associated with differences in perceptual criteria. For example, the difference in perceptual criterion could be confined to judgments of pulse brightness alone. In that case, we would expect systematic individual differences in simultaneous brightness judgments and in magnitude estimates of pulse brightness, but not on the other two tasks. Alternatively, individual differences could have been restricted to the simultaneous brightness discrimination task alone, diminishing the finding of Bowen and Markell (1980) to the status of a methodological oddity. Finally, differences in perceptual criteria could affect responses to any temporally modulated stimulus. This would lead to systematic individual differences on each task in our battery, an outcome that could also have been caused by general neurophysiological differences.

Our observers were 30 Northwestern and Loyola undergraduates. First, we determined to which class -- Type A, B, or C -- each observer belonged. Observers showing high variability on the initial brightness judgments were excluded from further participation in the experiment, and observers were screened for visual acuity of 6/6 or better using a Bausch and Lomb orthorator. Observers were also screened for normal color vision, using the Dvorine Pseudo-Isochromatic plates. Of the observers remaining in the pool, 11 were selected to participate in the magnitude estimation, flicker sensitivity and motion sensitivity experiments. All three Type C observers in the pool participated in the full experiment; four Type A and four Type B observers were selected at random.

We used the following criterion to classify observers (Bowen & Markell, 1980). Temporal brightness enhancement was deemed to occur for either asynchrony condition if at any shorter pulse duration the function was at 30% or less "longer pulse judged brighter," because 6 trials of 20 is significantly lower ($p < .057$) than 50% for a binomial distribution with an assumed probability of responding "longer pulse brighter" of 0.5. For observers classified as Type A, then, temporal brightness enhancement occurs for both asynchrony conditions; for Type B, enhancement is evident for the simultaneous offset condition, but not for simultaneous onset; and for Type C, enhancement does not occur under either asynchrony condition.

Our pool of 30 observers consisted of roughly 47%

Type A, 43% Type B, and 10% Type C.

The occurrence of temporal brightness enhancement in magnitude estimation data is indicated by a peak in the function at intermediate durations (Raab, 1962). Type A observers exhibit a pronounced peak at 63 msec, thus showing the Broca-Sulzer effect for judgments of the brightness of single pulses of light. The data of Type C observers indicate that brightness increases with increasing duration, without an obvious peak at any duration in the range we tested. Thus, observers who failed to show brightness enhancement with pairs of pulses also did not show enhancement with a single-stimulus method.

Type B observers show a brightness vs. duration function that is intermediate in form between those for Type A and Type C observers. There is some suggestion of a local peak in the function at 63 msec, but magnitude estimates of brightness are nearly constant from 100 to 500 msec and do not decline sharply in this range, as do the data for Type A observers. Inspection of individual magnitude estimation function indicates that two of the four Type B observers show a slightly peaked function, while the remaining two observers have functions that resemble the mean data for Type C observers.

In general, these results indicate that at least two classes of observers --Types A and C--can be clearly distinguished by their brightness judgments of single pulses of light. Therefore, the systematic differences among observers are not crucially dependent upon the simultaneous brightness discrimination procedure employed here in our previous study (Bowen & Markell, 1980).

For the observers tested, it is evident that there are no differences in sensitivity to full-field flicker. All three classes of observers manifest a characteristic band-pass flicker sensitivity function (Kelly, 1971) with a peak at 8 Hz and depressed sensitivity at low temporal frequencies. Also, the rate of decline in sensitivity from peak is similar at both high and low frequencies for all classes of observers. The three types of observers cannot be differentiated on the basis of flicker sensitivity.

At the slower, 0.5-Hz drift rate, there is extensive overlap among the three types in sensitivity measures. At the faster, 10-Hz drift rate, the data for one Type B observer showed unrealistically high sensitivity. Generally, however, it is not possible to distinguish clearly among the three classes of observers on the basis of their motion sensitivity.

Our study confirmed the existence of systematic individual differences in pulse brightness discrimination and showed that these differences also affect judgments of the brightness of a single light pulse. The present results leave us with the possibility that distinct classes of observers

use different perceptual criterion in judging the brightness of isolated pulses of light.

The hypothesis that observers differ in perceptual criteria makes us wonder about the developmental forces causing our three classes of observers to adopt different and characteristic ways of using the neurophysiological information generated by pulses of light. Also, we wonder whether these perceptual strategies might not be modifiable by experience or appropriate training. The possibility that observers differ in the way they utilize sensory information parallels Felsten and Wasserman's suggestion (1979) that an observer can base his sensory judgment on different features of his neural response, depending upon the psychophysical task confronting him or her.

The systematic differences in brightness perception that we found among observers may also have important practical consequences. For example, visual warning devices used in transportation systems can be designed specifically to capitalize on brightness enhancement effects (Boynton, 1967). But our results clearly show that such signal devices may be suboptimal for a large fraction of potential consumers. Consequently, designers of such systems may wish to explore the use of alternative temporal codes, for example, hybrid codes incorporating both long and short pulses of light.

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